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A H LEVIS ET AL. 17 OCT 86 LIDS-IR-1615

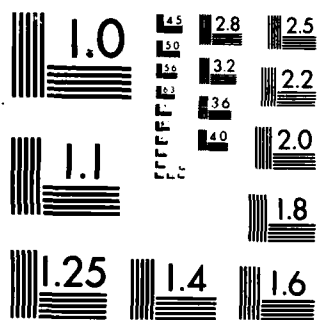
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CDR T. Jones, Code 121  
Mr. J. G. Smith, Code 1211  
Office of Naval Research  
800 N. Quincy Street  
Arlington, VA 22217-5000

Submitted by:

Alexander H. Levis  
Michael Athans

October 17, 1986

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## COMMAND AND CONTROL THEORY

### 1. PROJECT OBJECTIVES

→ The main goal of this research is to start bridging the gap between mathematical theories of command and control and empirical studies. More specifically, the goal is to develop theories on the one hand and to model experimental paradigms on the other, so that realistic problems in command and control ( $C^2$ ) can be studied prior to the design of experiments and the collection of relevant data.

The research program undertaken for this project has three main objectives:

- (a) 1) The extension of a mathematical theory of  $C^2$  organizations so that it can be used to design an experimental program;
- (b) 2) The further development of an analytical methodology for measures of effectiveness, and
- (c) 3) The investigation of organizational architectures for distributed battle management (many weapons on many targets resource allocation problems).

The unifying theme of this research is the concept of distributed information processing and decisionmaking. The emphasis is on the development of models and basic analytical tools that would lead to the design of an experimental program as contrasted to ad hoc experimentation.

The project draws upon and contributes to the theoretical developments on naval distributed tactical decisionmaking (DTDM) being pursued in parallel under ONR Contract No. N00014-84-K-0519. The co-existence of these two programs has made it possible to undertake long-range, basic

research on fundamental issues and problems in command and control.

## 2. STATEMENT OF WORK

The research program has been organized into five tasks, four that address the research objectives and a fifth that addresses the question of disseminating the results of this project both directly to the members of the Basic Research Group of the Technical Panel on C<sup>3</sup> of the Joint Directors of Laboratories and to the C<sup>3</sup> community at large through publications and presentations.

### 2.1 RESEARCH TASKS

#### TASK 1: Development of Computer-Aided Design System

- 1.1 Develop the specifications for the Computer-Aided Design System. Specifically, design the data base, the architecture generator, the performance-workload locus module, and the analysis and evaluation module. The system should be able to handle a generic five member, three echelon organization.
- 1.2 Implement the design developed in Task 1.1. Design the graphics module to be used in presenting the performance-workload locus and its projections as well as the loci obtained from the analysis and evaluation module.
- 1.3 Design and implement the user interface. Use the Petri Net formalism for the specification of the interactions between organization members and the design of protocols.

#### TASK 2: Command and Control Organization Design and Evaluation

- 2.1 Develop and implement a set of tasks, as well as sets of

information processing (situation assessment) and decisionmaking (response selection) algorithms for use with the decisionmaker models. These tasks and algorithms should be appropriate to future experimental efforts.

- 2.2 Use organizations with up to five members to exercise and test the CAD system developed in Task 1.
- 2.3 Analyze and evaluate command and control organizational architectures using the CAD system. Begin developing hypotheses that can be tested through experimental efforts.
- 2.4 Incorporate in the design system and in the analysis module the theoretical results obtained from parallel research projects.

TASK 3: C<sup>3</sup> Organizations and Architectures for Distributed Battle Management

- 3.1 Develop a unified theory for complex engagements of several weapons against several targets. Assume imperfect defensive weapons systems so that the elemental "one-on-one" kill probability is non-unity. Also assume imperfect defensive surveillance so that the target/decoy discrimination probability is non-unity.
- 3.2 Develop several "many-on-many" engagement strategies and evaluate their impact upon decentralized C<sup>3</sup> system requirements and architectures. Develop the necessary tools so as to design distributed C<sup>3</sup> architectures compatible with the engagement strategies.
- 3.3 Illustrate the tactical doctrine and C<sup>3</sup> interface requirements via computer simulations. Develop hypotheses that could be tested in the field.

#### TASK 4: Measures of Effectiveness

- 4.1 Conceptual Development. Develop and refine the concepts and definitions of measures of effectiveness (MOEs), measures of performance (MOPs), and system/mission parameters. Interpret the concept of measure of force effectiveness (MOFE) as a global effectiveness measure in the context of C<sup>3</sup> systems.
- 4.2 Implementation of the Methodology. Develop a quantitative framework where models of various types can be used to estimate measures of performance (MOPs). Develop analytical, computational and graphical tools for measuring effectiveness (MOEs). Begin the implementation of these techniques on the same workstation used for Task 1 with the objective of developing a system based on MOE evaluation that can be used as an aid in system development and selection. Note that many of the software utilities to be developed are common to Tasks 1 and 4.
- 4.3 Application of the Methodology. Illustrate the various conceptual and technical developments with examples drawn from actual or planned C<sup>3</sup> systems. Apply the methodology to an evolving C<sup>3</sup> system. While motivated by real systems, the applications will be described in generic terms.

#### TASK 5: Information Dissemination

- 5.1 Participate in technical sessions of the Basic Research Group to be held approximately once per calendar quarter.
- 5.2 Present the research results at technical conferences and meetings and publish articles in archival journals.



### 3. PROGRESS REPORT

During the first year of the project, emphasis was placed on the extension of the theory and the development of computational and graphical tools to be used in the design of experiments. One Master's Thesis was completed in May 1986, two in August, 1986; and a fourth one in late September, 1986. All four are being published as Reports of the Laboratory for Information and Decision Systems.

#### 3.1 Development of Computer-Aided Design System

The computer aided design system being developed consists of four major components:

A Data Base which is used to store basic organizational architectures and the corresponding loci of its Measures of Performance (MOPs).

The Architecture Generator which constructs feasible organizational forms using the Petri Net formalism.

The Locus module that computes and constructs the performance-workload locus of an organizational form that is carrying out a given task.

The Analysis and Evaluation Module contains algorithms for the analysis of organizational architectures and their evaluation.

Highlights of progress made during the reporting period follow.

##### 3.1.1 Analytical Generation of Organizational Architectures

A methodology for generating the complete set of feasible organizational architectures is being developed by Pascal Remy under the supervision of Dr. A. H. Levis. It is based on the recent theoretical developments in this project and the related ONR DTDM Project.

The organizational design problem is posed for a well defined class of architectures - those for which the interactions between decisionmakers can be represented by acyclical directed graphs. These architectures represent distributed decisionmaking organizations performing well-defined tasks.

The mathematical formulation of the problem is based on the Petri Net description of the organizational structure. The dimensionality of the combinatorial problem has been reduced by utilizing the notion of information paths within the organization. A number of concepts have been introduced, such as the maximally connected organizations or structures and the minimally connected ones. These concepts are used to bound the set of feasible organizational forms. Very recently, the problem has been recast in the context of lattice theory, which opens up a wealth of mathematical results that can be exploited.

An algorithm has been developed for generating the alternative organizational structures that meet both general structural constraints, as well as constraints that are specific to the application being considered.

The approach is described in a recent technical paper (see #1 in Section 5.2) and is currently being documented in detail in P. Remy's Master's Thesis, expected to be completed in December 1986.

The software module has been completed and has been implemented as part of the Architecture Generator on the workstation, which consists of an IBM PC/AT with a 20MB hard disk drive and the Professional Graphics Card/Adaptor and Monitor.

### 3.1.2 Graphical Generation of Organizational Architectures

The second component of the Architecture Generator is being designed and implemented by John Kyratzoglou under the supervision of Dr. A. H. Levis. In this task, an interactive system is being developed that allows the user to create graphically, using Petri Net symbology, an

organizational structure on the screen under keyboard cursor control or mouse control. The latter has not been implemented yet.

The user can select one of the standard symbols of Petri Nets (places or circle nodes, bars or transition nodes, and links or connectors, as well as a special transition node designating a decision node) and can begin connecting it to other nodes, thus creating an arbitrary organizational architecture. The underlying algorithms interpret the graphical representation of the architecture and create its analytical description in the form of flow or interconnection matrices that characterize Petri Nets. The user can also design and store organizational units and then retrieve them in order to construct more complex organizational structures. All the software use a standardized data structure that is consistent with the analytical theory of Petri Nets.

The basic system has been designed and implemented. Indeed, in early August, it was demonstrated for the first time to a group of faculty and students from the Naval Postgraduate School.

Current tasks include the intergration of this software with the analytical design system described at the beginning of the section so that the feasible organizational architectures obtained from analytical considerations can be depicted graphically as a Petri Net on the monitor. In this subtask, the size of the organization has been limited to five decisionmakers in order to keep the extent of the programming effort under control and in order not to exceed the limitations of the IBM PC/AT. However, there are no theoretical or conceptual limitations — only practical ones — to the size of the organizations being considered. At the same time, J. Kyratzoglou has started documenting the system design as part of the thesis requirements for the Mechanical Engineer's degree (expected June 87).

### 3.2 Command and Control Organization Design and Evaluation

#### 3.2.1 Time-Related Performance Measures

The theoretical developments thus far in organization theory were focused on steady state characteristics and measures of performance. However,  $C^2$  organizations operate in a rapidly changing environment and, therefore, measures are required that take into account explicitly the dynamics of the command and control process. In the first research task addressing this issue, carried out by Herve Hillion under the supervision of Dr. A. H. Levis, the model of the decisionmaking organization has been enhanced by the use of Timed Petri Nets, both deterministic and stochastic. The organizations can be modeled now as asynchronous concurrent systems with resource and throughput constraints. This version of the model allows the evaluation of time-related performance measures: (a) the maximum throughput rate, defined as the maximum processing rate achievable by the organization, and the execution schedule, which determines the earliest instants at which the different information processing and decisionmaking operations can occur. This result, in turn, leads directly to the optimal protocol for the organization. These quantities, the throughput rate and the schedule, are expressed as functions of the resources (e.g., processing resources) and the time needed for each operation. These parameters are specific to each architecture and task that is to be performed.

The characterization that is obtained makes it possible to compare different organizational designs with respect to their time-related performance measures and to analyze and modify existing designs by changing protocols so as to improve performance.

The analytical results have been used to develop and implement algorithms that will be integrated in the near future with the steady-state performance measures in the Analysis and Evaluation Module.

The results of this task have been documented in the Master's Thesis of H. Hillion (see #3 in Section 5.1) which has been issued as a LIDS report.

### 3.2.2 Organizational Designs

In accordance with Subtask 2.2, two different five person organizations have been modeled to serve as the basis for exercising the computer-aided design system and as the starting point for developing an experimental paradigm. The first organization is a general one with two decisionmakers who process overlapping sensor data (situation assessment), two who control different resources (weapons officers) and a commander who oversees and controls the whole operation. This example is used by P. Remy as the illustrative example in generating alternative organizational forms.

The second example is drawn from work done by Scott Weingaertner. It is a model of the five person ship control party of an attack submarine as configured for responding to emergencies. While the original effort was done under the auspices of the Charles Stark Draper Laboratory, Weingaertner is now adapting this work to create a second general example that can be used for testing the various components of the design system. The model has been documented in Weingaertner Master's Thesis (#4 in Section 5.1). It has also been used by Hillion in illustrating time-related measures of performance.

### 3.3 C<sup>3</sup> Organizations and Architectures for Distributed Battle Management

The long-range goal of this research is to understand basic issues associated with Battle Management C3 (BM/C3) architectures associated with many weapons engaging several targets. The defensive weapons are assumed imperfect, and the targets may have a finite probability of being decoys. Thus, the problem is one of wise Weapon-to-Target (WTA) assignment strategies, and their interface with other BM/C3 functions. We also seek the evaluation of centralized, decentralized, and distributed BM/C3 architectures that support such "many-on-many" engagements.

The major emphasis of the research during the past year has been in the area of problem definition. Professor Athans studied the problem of optimizing the Weapon-to-Target (WTA) function which is at the heart of the "many-on-many" problem. Suppose that we have a total of  $M$  weapons which we are willing to commit against the total of  $N$  targets. At that most general level, the effectiveness of each weapon can be different against each target; this can be quantified by having a different kill probability  $p_{ij}$  for weapon  $j$  assigned against target  $i$  ( $j=1,2,\dots,M$ ;  $i=1,2,\dots,N$ ). The WTA function wishes to allocate the right weapons against the correct targets so as to minimize leakage, i.e., the expected number of surviving targets. Thus, if we adopt an optimization framework we wish to minimize the leak  $L$  which is given by

$$L = \sum_{i=1}^N \prod_{j=1}^M (1 - p_{ij} x_{ij}) \quad (1)$$

by selecting optimally the  $M \cdot N$  allocation decision variables  $x_{ij}$ , each of which is either 0 or 1. Thus,  $x_{ij} = 1$  if the  $j$ -th weapon is assigned to the  $i$ -th target and 0 otherwise and

$$\sum_{i=1}^N x_{ij} = 1, \quad j = 1, 2, \dots, M \quad (2)$$

which simply states that each weapon can only engage a single target.

The solution of this optimization problem for the WTA function is very difficult, because it has a strong combinatorial flavor and in fact it has been proven to be NP-complete by Lloyd and Witsenhausen in 1986. Part of the complexity relates to the fact that the kill probabilities  $p_{ij}$  are different. If the kill probabilities are the same, i.e.,  $p_{ij} = p$  for all  $i$  and  $j$ , then the optimal solution is easy and it requires the maximally uniform assignment of the weapons among the targets. The problem is

inherently hard even in the special case that the kill probabilities depend only on the weapons but not the targets, i.e.,  $p_{ij}$  is independent of  $i$ .

The inherent complexity of the WTA optimization problem suggests that it may be advisable to decompose the centralized WTA function into subfunctions, and accept the collective decisions of the WTA subfunctions as a suboptimal solution to the centralized WTA problem. For example, one can split both the targets and the weapons into subsets so that for each subset the kill probabilities are approximately the same and use a maximally uniform allocation within this subset. Indeed this may turn out to be a reasonable starting point in the definition of distributed BM/C3 architectures that support the WTA function.

These additional issues are being studied by Mr. J. Walton who joined the project in June 1986. Mr. Walton's doctoral thesis research, under the supervision of Professor M. Athans, will examine additional tradeoffs that arise from decoy considerations, vulnerability of BM/C3 to enemy countermeasures, and delays in decision execution. We foresee highly nontrivial tradeoffs as we move from centralized to distributed and then to purely decentralized (or autonomous) BM/C3 architectures. In particular:

- o Optimal weapon resource utilization deteriorates with increased distribution; however, such degradation will be strongly dependent upon the effectiveness of one-on-one engagements (the kill probabilities  $p_{ij}$  defined above).
- o The overall vulnerability of the BM/C3 functions will reduce as the degree of its distribution increases.
- o The communications requirements for coordination will increase as we distribute the BM/C3 functions more and more.
- o The complexity of the coordination strategies will increase as the degree of distribution increases.
- o The delay in executing a local BM/C3 function will decrease in distributed architectures, simply because each subfunction will have to handle fewer targets and weapons.

To what extent the improvement in survivability and reduced delays are counterbalanced by increases in communication/coordination and resource misutilization remains a problem for future research.

No formal documentation exists as yet. The Ph.D. thesis of J. Walton is scheduled for completion in 1988.

### 3.4 Measures of Effectiveness

#### 3.4.1 Conceptual Development

In the last several years, a series of workshops have been held under the auspices of several DOD organizations in an effort to develop generic tools for evaluating command and control systems. The concepts and definitions that have been evolving from these workshops have been used to re-examine the System Effectiveness Analysis (SEA) methodology - a quantitative methodology for modeling and computing measures of performance (MOPs) and measures of effectiveness (MOEs) for  $C^3$  systems. The results of this effort (Task 4.1) have been documented in the paper "Modeling and Measuring Effectiveness of  $C^3$  Systems" by A. H. Levis (#2 in Section 5.2).

#### 3.4.2 Methodological Development

One of the key problems in  $C^3$  system design and evaluation is that it is difficult to carry out experiments under real operating conditions. One approach is to design and run experiments in large testbeds that combine computer simulations, men-in-the-loop, and actual operational components. However, the problem still remains of how to design the smallest number of experiments that enables one to evaluate the effectiveness of the actual system. This research problem was investigated by Philippe Martin under the supervision of Dr. A. H. Levis with partial support by this contract.

The approach taken is based on the assumption that the testbed is a faithful representation of the actual system to be evaluated. In addition, a simplified model (e.g., a simulation model or an analytical model) of the



system is considered. This simple model can be exercised under a wide variety of conditions and scenarios to obtain values of the measures of performance of the system. If these are plotted in the space of performance measures (MOPs), a locus is obtained that characterizes the system, as represented by the model (Figure 1). From this locus, one can determine the extreme values that the vector of MOPs can take. To each such vector corresponds some set of parameters and/or a scenario. An algorithm has been developed, based on singular value decomposition, that "inverts" the mapping from the parameter space to the MOP space, i.e., inverts the "model" of the system. The sets of parameters obtained in this manner become the sets of experimental conditions under which the testbed is exercised. Clearly, the MOP values obtained from the testbed do not coincide with the values obtained from the model. A linear transformation is obtained that maps the model MOP points to the experimentally obtained points. Then this transformation is used to obtain, from the model MOP locus, the whole locus of the system represented by the testbed. In the next step, the System Effectiveness Analysis methodology is applied to the testbed locus to calculate the MOEs of the system. If the system is an evolving one, i.e., one that is changed over time through the introduction of new technologies or new components, then the methodology can be used to plan the sequence of enhancements so that the system's effectiveness increases over time.

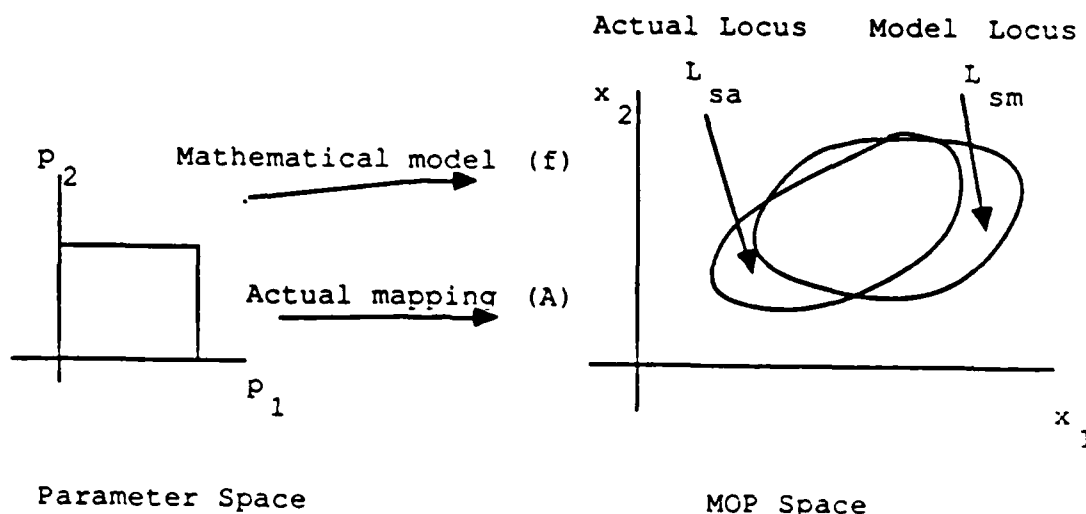


Figure 1. Actual and Model Loci

The theoretical developments were illustrated through application to the Identification Friend Foe Neutral (IFFN) Joint Test Bed that is operational at Kirtland AFB.

The results of this research subtask (Subtask 4.3) have been documented in Martin's SM Thesis which has published as a LIDS Report (#2 in Section 5.1).

### 3.4.3 Implementation of the Methodology

System Effectiveness Analysis (SEA) is a methodology for assessing the effectiveness of a system by constructing and evaluating loci that represent the performance characteristics of the system and the requirements of the task to be performed. A computer graphics program has been designed and implemented on the workstation by Christine M. Bohner, under the supervision of Dr. A. H. Levis. This program constructs three dimensional projections of higher dimensional surfaces or loci. The program allows the user to view the loci in different dimensions which serves as an aid in analysis. To demonstrate the use of the program, the effectiveness of a particular  $C^3$  system was analyzed; a battalion level fire direction systems. Two aspects of the system were studied: the effect of adding more components to the system, and the sensitivity of the overall effectiveness to different errors within the measuring equipment of the system. The graphics system was used to generate the plots of the system loci and to evaluate its performance.

The software that has been developed has been used also in the analysis and evaluation of organizations. It is the key component in the methodology for computer aided design and evaluation of organizations (Task 1.2).

The results of this work have been documented in C.M. Bohner's SM Thesis which has been published as a LIDS Report (#1 in Section 5.1).

#### 4.0 RESEARCH PERSONEL

Dr. Alexander H. Levis, Principal Investigator

Professor Michael Athans

Ms. Christine M. Bohner,	Research Assistant	(Graduated; SM degree)
Mr. Philippe J.F. Martin,	Research Assistant	(Graduated; SM degree)
Mr. Herve P. Hillion,	Research Assistant	(Graduated: SM degree)
Mr. John Kyratzoglou,	Research Assistant	(ME Candidate)
Mr. Pascal P. Remy,	Research Assistant	(SM Candidate)
Mr. James Walton,	Research Assistant	(Ph.D. Candidate)
Mr. Scott Weingaertner	Research Assistant	(MS Candidate)

Following an open search, Dr. Jeff Casey joined MIT on September 2, 1986 as a Research Scientist. Dr. Casey has just completed the Ph.D. degree in cognitive psychology at the University of Wisconsin; his primary responsibility will be the design of the experimental program.

#### 5.0 INFORMATION DISSEMINATION

The following documents were issued as Laboratory Technical Reports or as Technical Papers. There were submitted to ONR, to the Basic Research Group of JDL Panel on C<sup>3</sup> and to the distribution list specified in the contract. Some aspects of the work contained in these reports were supported by other related projects, such as the one from the Office of Naval Research on Distributed Tactical Decisionmaking (N00014-84-K-0519).

##### 5.1 Theses/Technical Reports

1. C. M. Bohner, "Computer Graphics for System Effectiveness Analysis," LIDS-TH-1573, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, July 1986.
2. P.J.F. Martin, "Large Scale C<sup>3</sup> Systems: Experimental Design and System Improvement, LIDS-TH-1580, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, August 1986.

3. H. P. Hillion, "Performance Evaluation of Decisionmaking Organizations Using Timed Petri Nets," LIDS-TH-1590, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, August 1986.
4. S. T. Weingaertner, "A Model of Submarine Emergency Decisionmaking and Decision Aiding," LIDS-TH-1612, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, September 1986.

## 5.2 Technical Papers

1. P. Remy, A. H. Levis, and Y.-Y. Jin, "Delays in Acyclical Distributed Decisionmaking Organizations," LIDS-P-1528, Laboratory for Information and Decision Systems, MIT, January 1986. (Accepted for presentation at the 10th World Congress of the International Federation on Automatic Control, Munich, FRG, July 1987).
2. A. H. Levis, "Modeling the Measuring Effectiveness of  $C^3$  Systems," LIDS-P-1608, Laboratory for Information and Decision Systems, MIT, September 1986. (To be presented as an invited paper at the Seventh Annual AFCEA European Symposium on October 30, 1986).
3. M. Athans, "Command -and-Control Theory: A Challenge to Control Science" LIDS-P-1584, Laboratory for Information and Decision Systems, MIT, September 1986; paper has been submitted for publication to the IEE Transactions on Automatic Control.

## 5.3 Technical Interactions

On August 11 and 12, 1986, 8 faculty and students from the  $C^3$  Curriculum of the Naval Postgraduate School visited the MIT Laboratory for Information and Decision Systems where they had an in-depth presentation of the research results in anticipation of joint efforts in carrying out the experimental program.

In June 1986, Dr. Levis presented the first results on the generation of alternative organizational forms at the 9th MIT/ONR Workshop on  $C^3$  Systems.

Dr. Levis attended four meetings of the Basic Research Group in accordance with contractual requirements in which he briefed the Group on the progress of the research effort. The meetings were held at the

Naval Ocean Systems Center, At Ft. Monmouth, and at the National Defense University.

Dr. Levis participated in the second workshop on Measures of Effectiveness for Command and Control Systems held at the Naval Postgraduate School in January 1986. His involvement in this workshop led to the use of the IFFN testbed as the illustrative example in Martin's thesis.

Dr. Levis and Mr. P. Martin participated in a meeting organized by Studies and Analyses, USAF, to discuss the applicability of the work to the experimental program of the IFFN Joint testbed (US Army, US Air Force).

These interactions are considered essential for presenting the results of basic, fundamental research to the C<sup>3</sup> community and for receiving feedback -- comments and suggestions -- that increase the relevance of the work.

## 6.0 FUTURE PLANS

After a slow start, the project is now fully staffed and work is progressing on schedule. In accordance with recent discussions with CDR T. Jones, in addition to the annual reports and aperiodic technical reports and papers, brief quarterly progress reports will be submitted. The first quarterly report will be issued on December 15, 1986.

FIN